# Biological Evaluation of Hemlock Woolly Adelgid At The Flight 93 National Memorial, Somerset County, Pennsylvania


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Prepared for
National Park Service
Flight 93 National Memorial
August 2012 (3413-NA-12-04)

## Abstract

On August 29-31, 2012 personnel from the USDA Forest Service, Northeastern Area, Forest Health Protection, Morgantown, WV. Field Office conducted a survey to evaluate hemlock woolly adelgid (HWA), *Adelges tsugae* Annand (Hemiptera: Adelgidae), population densities at the Flight 93 National Memorial in southwestern Pennsylvania. The purpose of the survey was to assess the need for treatment in the hemlock grove area of the crash site. Hemlock woolly adelgid is present throughout the survey areas at high levels. Since HWA has been found in the hemlock grove area, it is recommend that a comprehensive hemlock management plan be developed and a chemical suppression/prevention treatment plan be put into place to protect eastern hemlock trees. The release of predatory beetles is also recommended as a potential long-term biological control strategy of HWA.

## Purpose and Need

The Morgantown Field Office (MFO) received a request for a site visit from Keith Newlin, Deputy Superintendent of the Western Pennsylvania Parks, National Park Service whose staff recently observed hemlock woolly adelgid activity within the hemlock grove of the Flight 93 memorial crash site. This project was undertaken by the MFO to address this request and to identify any significant issues that might occur as a result of hemlock woolly adelgid within the Flight 93 memorial hemlock grove.

## Project Location/Description

The Flight 93 National Memorial is located in southwestern Pennsylvania in Somerset county (40º04'N, -78º53'W). The Memorial covers approximately 2,200 acres of which 1,025 acres are forested (figure 1). The Memorial lies in the Appalachian mixed hardwood region (Rhoads and Block, 2005) within the oak-hickory ecological forest type, which is associated with oaks (*Quercus*) yellow popular (*Liriodendron tulipifera* L.) and northern hardwood forest cover type (Smith et al. 1983). The site has been extensively modified by human activity related to the mining of bituminous coal (USDI, 2007).

The crash site is located within a fenced area (fenced in 2001) near the southern end of the memorial, and contains a number of building and structures (USDI, 2007). This area covers 38 acres of which 18 acres are forested (figure 2.). The hemlock grove is enclosed within the fenced area and covers 11 acres (figure 3). Soils within the forested area of the crash site are classified as Atkins, Brinkerton and Cavode silt loams (NRCS, 2012). These soils are moderately to poorly drained with similar topographic relief (<3% slope) and shallow water table (<18 inches; (NRCS, 2012).

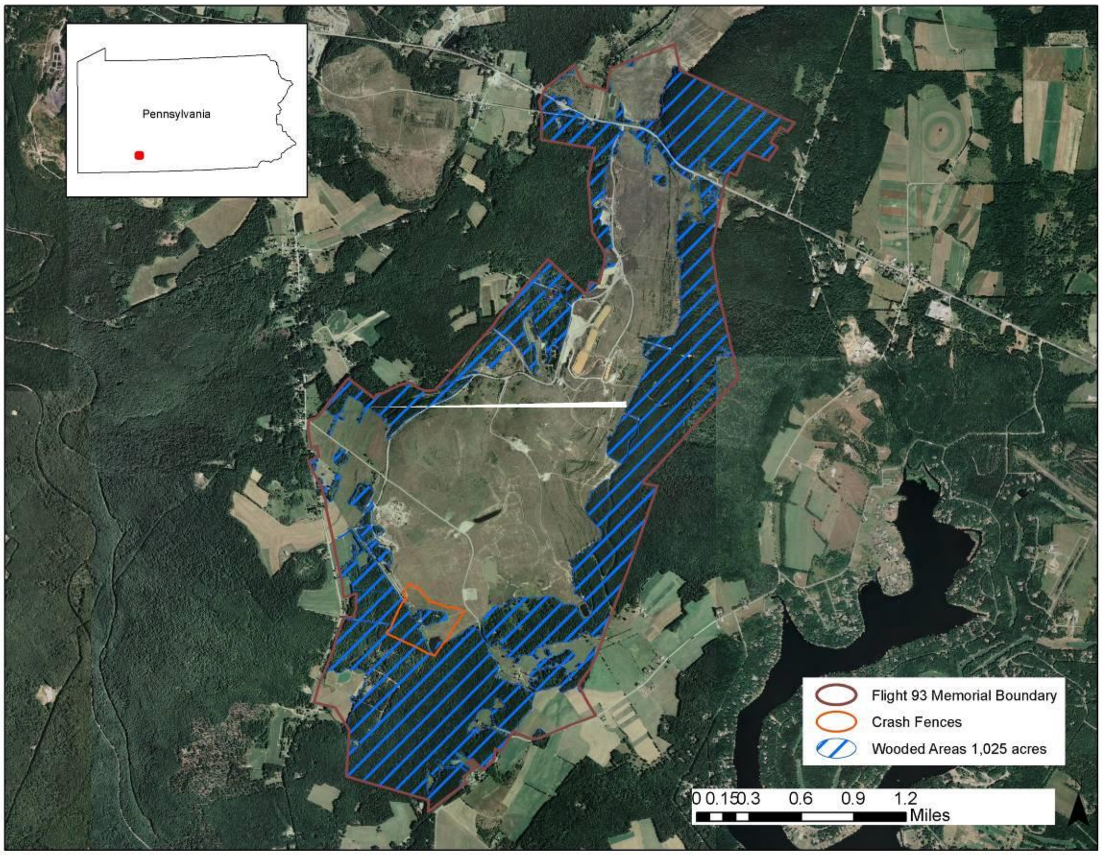


**Figure 1**. Flight 93 National Memorial, Somerset County, Pennsylvania.

## Project Objectives

The objectives for this evaluation were to 1) assess the location of eastern hemlock (*Tsuga canadensis*) within the crash site, 2) inventory the physical characteristics of the trees within the hemlock grove 3) evaluate the extent and impact of hemlock woolly adelgid, and 4) determine the need for management activities within the hemlock grove of the Flight 93 National Memorial.

## Project Methods

### *ARCMAP data*

We used ARCMAP® data provide by U.S. Department of the Interior, National Park Service to identify the administrative boundary area and crash site (Callahan, 2012). These boundary areas were then overlaid with National Agricultural Imagery Program (NAIP) data and Google earth imagery, which was used to digitize tree cover, calculate acreage, and select survey points.


**Figure 2**. Flight 93 National Memorial crash site, Somerset County, Pennsylvania.

*Inventory plots and monitoring trees*

To inventory and assess HWA populations we established ten, 1/20 th acre (26.3 ft. radius) fixed radius overstory plots within the hemlock grove. Plot locations were randomly selected using ARCMAP and monumented with wooden stakes. Tree and sapling data were collected on all trees at least 1.0 inches in diameter at breast height (dbh; 4.5 ft. above the ground; USDA 2001) within each 1/20 th acre plot. For each tree (≥ 5.0 inches dbh) we recorded species, crown class (i.e. dominant, co-dominant, intermediate, and overtopped; USDA 2001), and dbh. For all saplings (≥ 1 inch but < 5 inches dbh) we recorded species, and dbh. We assessed seedlings (0.5 ft. tall to < 1 in. dbh) on a nested 1/500 th acre (5.2 ft. radius) fixed radius mircoplots within each overstory plot. On each microplot we recorded species, size class, and tallied the number of seedlings present. Presence of HWA and other insect pests was noted throughout the stand during this survey. At each plot location five overstory hemlock trees (50 total) were randomly selected for visual evaluation and monitoring. For each of these trees we recorded dieback (none, light 1-15 %, moderate 16-30 %, heavy >30 %), and crown transparency (< 30 %, 31-50 %, >50 %; USDA 1999).

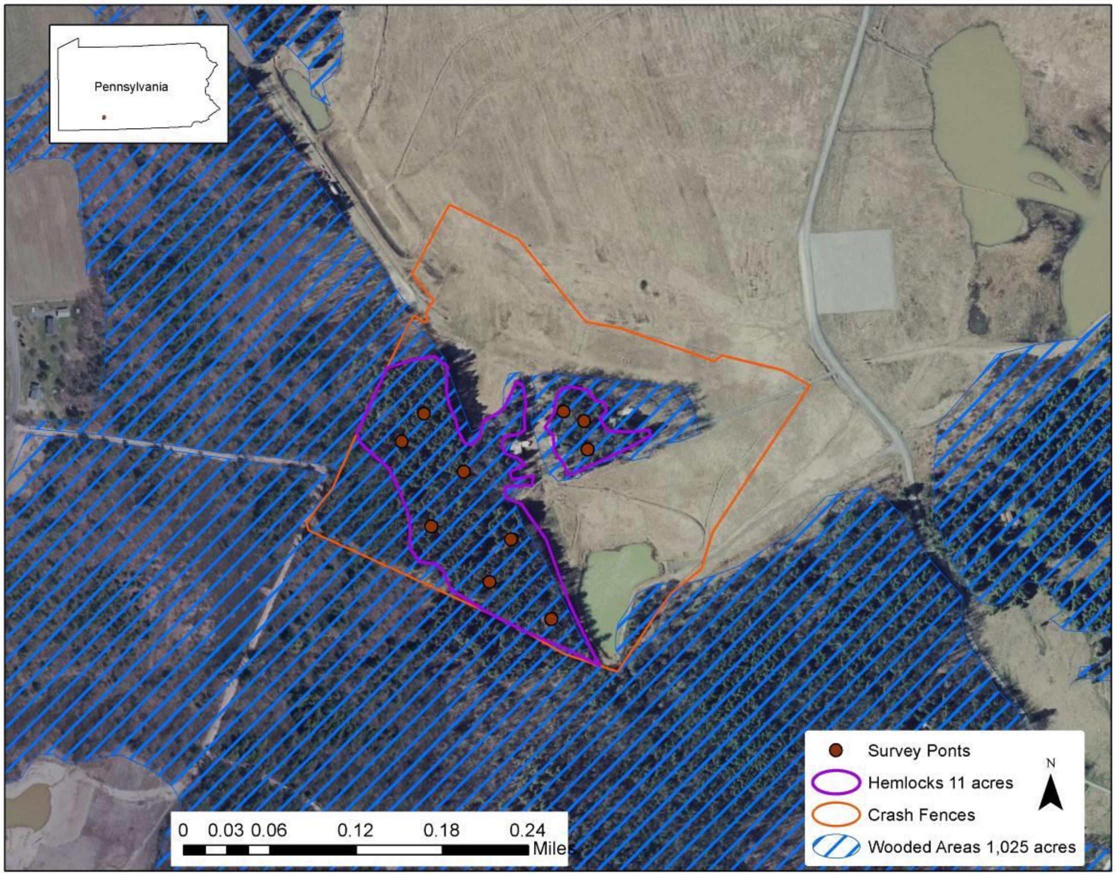


**Figure 3**. Hemlock grove and survey plot locations, Flight 93 National Memorial, Somerset County, Pennsylvania.

*Data analysis*

Data were compiled across the 11 acre hemlock grove according to tree condition by species and size. Individual tree basal area was determined using the constant .0054542 multiplied by diameter at breast height (DBH) squared. Basal area was summed by species for each plot, divided by the area sampled, and then multiplied by a per acre conversion factor. Basal area was calculated for all species. Trees per acre (TPA) were determined for each species in the grove. This number was calculated by taking the number of stems within the area sampled, divided by the area sampled, and then multiplied by the per acre conversion factor. The quadratic stand diameter (QSD) and quadratic mean diameter were calculated as the square root of the sum of the diameters at breast height (4.5 feet above ground) of each individual tree and by each plot tree divided by the total number of trees (Curtis et al. 2000). All trees ≥4.5 inches DBH were used to compute TPA, QSD, and BA/AC.

## Results

*Species composition and basal area*

Total basal area including living and standing dead trees in the hemlock grove was 250.6 ft²/acre with a stem density of 290 TPA and a QSD of 17.1 inches. The average living basal area was 237.6 ft²/acre with a stem density of 252 TPA and a QSD of 11.8 inches (table 1). Eastern hemlock accounted for an average of 155.1ft²/acre of live basal area with a density of 182 TPA and a QSD of 11.3 (table 2), other species accounted for an additional 82.5 ft²/acre of basal area with a density of 70 TPA and a QSD of 12.2 inches, represented in decreasing order by red maple (*Acer rubrum*), black cherry (*Prunus serotina)*, black birch (*Betula lenta*), northern red oak (*Quercus rubra*), yellow birch (*Betula alleghaniensis*), sugar maple (*Acer saccharum*). Shrub species present included rosebud rhododendron (*Rhododendron maximum*), greenbrier (*Smilax sp*.) and poison ivy (toxicodendron radicans). Herbaceous species such as fern and sedges (Carex spp.) were also observed.

**Table 1.** Number of trees, basal area, trees per acre and quadratic mean diameter (QMD) live and dead stems for all species on each plot within the hemlock grove, Flight 93 National Memorial, Somerset County, Pennsylvania.

| | Live | | | | Dead | | | |
|---|---|---|---|---|---|---|---|---|
| **Plot#** | **Tally Trees** | **BA/AC** | **TPA** | **QMD** | **Tally Trees** | **BA/AC** | **TPA** | **QMD** |
| 1 | 5 | 209.6 | 100 | 11.4 | 0.0 | 0.0 | 0 | 0.0 |
| 2 | 14 | 268.4 | 280 | 12.4 | 0.0 | 0.0 | 0 | 0.0 |
| 3 | 9 | 285.0 | 180 | 16.3 | 1.0 | 55.7 | 20 | 22.6 |
| 4 | 16 | 260.7 | 320 | 11.0 | 1.0 | 5.5 | 20 | 7.1 |
| 5 | 16 | 239.6 | 320 | 10.9 | 7.0 | 26.8 | 140 | 5.9 |
| 6 | 11 | 205.9 | 220 | 12.5 | 4.0 | 21.2 | 80 | 6.9 |
| 7 | 10 | 161.1 | 200 | 11.4 | 4.0 | 15.4 | 80 | 5.0 |
| 8 | 12 | 79.4 | 240 | 7.3 | 2.0 | 5.6 | 40 | 5.1 |
| 9 | 18 | 287.3 | 360 | 11.3 | 0.0 | 0.0 | 0 | 0.0 |
| 10 | 15 | 379.2 | 300 | 13.9 | 0.0 | 0.0 | 0 | 0.0 |
| **Average** | **12.6** | **237.6** | **252** | **11.8** | **1.9** | **13.0** | **38** | **5.3** |

*Mortality*

Total standing dead basal area in the hemlock grove was 13.0 ft²/acre with a stem density of 38 TPA and QSD of 8.7 inches. The majority of the dead trees were eastern hemlock, which ranged in size from 5-22 inches in dbh. Eastern hemlock mortality represented 7.7 % of the total basal area and 100 % of the TPA of standing dead.

*Insect activity data*

Hemlock woolly adelgid was observed in three of the 10 overstory plots surveyed, and in 12 of the 50 monitoring trees. No other hemlock pests were observed (e.g. scale insects, mites). Unfortunately, it is often difficult to determine if tall overstory hemlock trees have been effected by HWA because their branches are simply too high to see, even with the use of binoculars. Thirty-four percent of the hemlock trees that could be surveyed were infested with HWA. HWA was observed in 5.43 % of the codominant trees and 23.1 % of the suppressed trees.

**Table 2.** Number of trees, basal area, trees per acre and quadratic mean diameter **(**QMD**)** of living and dead stems of eastern hemlock for the hemlock grove, Flight 93 National Memorial, Somerset County, Pennsylvania**.**

| | **Live** | | | | **Dead** | | | |
|---|---|---|---|---|---|---|---|---|
| **Plot#** | **Tally Trees** | **BA/AC** | **TPA** | **QMD** | **Tally Trees** | **BA/AC** | **TPA** | **QMD** |
| 1 | 2 | 23.1 | 40 | 9.4 | 0.0 | 0.0 | 0 | 0.0 |
| 2 | 4 | 46.9 | 80 | 10.2 | 0.0 | 0.0 | 0 | 0.0 |
| 3 | 7 | 199.0 | 140 | 15.3 | 1.0 | 55.7 | 20 | 22.6 |
| 4 | 15 | 203.5 | 300 | 10.2 | 1.0 | 5.5 | 20 | 7.1 |
| 5 | 16 | 239.6 | 320 | 10.9 | 7.0 | 26.8 | 140 | 5.9 |
| 6 | 6 | 77.3 | 120 | 10.2 | 4.0 | 21.2 | 80 | 6.9 |
| 7 | 7 | 140.6 | 140 | 12.9 | 3.0 | 15.4 | 60 | 6.7 |
| 8 | 5 | 50.8 | 100 | 9.0 | 2.0 | 5.6 | 40 | 5.1 |
| 9 | 14 | 190.7 | 280 | 10.7 | 0.0 | 0.0 | 0 | 0.0 |
| 10 | 15 | 379.2 | 300 | 13.9 | 1.0 | 1.2 | 20 | 3.3 |
| **Average** | **9.1** | **155.1** | **182** | **11.3** | **2** | **13.1** | **38** | **5.8** |

*Monitoring Trees*

Of the 50 eastern hemlock monitoring trees surveyed, 90 % are experiencing some level of dieback. Two percent are showing a high level of dieback, 16 % have a medium level of dieback, 72 % are showing a light level of dieback and 10 % have no dieback. Ninety-six percent of the monitoring trees had <30 % transparency, the other four percent had 31-51 % transparency.

*Seedling Densities*

There is an average of 1525 stems per acre of regeneration (< 0.5 feet tall; table 3). Red maple was found in four of the 10 plots and accounted for the majority of established regeneration with

a total of 5450 stems per acre (<0.5 feet tall). Eastern hemlock had the next highest regeneration rate in the under 0.5 foot tall size class with a total of 400 stems per acre. There is also a small component of sugar maple and black cherry in the under the under 0.5 foot tall size class (table 3). In the 0.5-1 foot tall size class eastern hemlock and red maple are equally represented (300 stems per acre), followed by green ash (*Fraxinus pennsylvanica;* 100 stems per acre) and black cherry (50 stems per acre). In the 1-3 feet size class green ash represented the largest component with, 400 stems per acre. In this class red and sugar maple were equally represented with 150 stems per acre followed by eastern hemlock (100 stems per acre) and Cucumber magnolia (*Magnolia acuminate*) and northern red oak with 50 stems per acre each. The only species in the 3-5 feet size class was green ash (50 stems per acre; table 3).

*Sapling densities*

There was an average of 29 saplings per acre (1-4.4 inches dbh; table 3). The majority of those saplings were eastern hemlock (70 stems per acre), followed by black birch (14 stems per acre) and red maple (two stems per acre).

**Table 3.** Seedling/sapling summary for the hemlock grove, Flight 93 National Memorial, Somerset County, Pennsylvania.

| | **Stems per Acre/Size Class** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Species** | **<0.5 feet** | **0.5-1 feet tall** | **1-3 feet** | **3-5 feet** | **<10ft<1in** | **1-4.4 inch** | **Total** |
| Eastern Hemlock | 400 | 300 | 100 | 0 | 0 | 70 | 870 |
| Red Maple | 5450 | 300 | 150 | 0 | 0 | 2 | 5902 |
| Sugar Maple | 150 | 0 | 150 | 0 | 0 | 0 | 300 |
| Green Ash | 0 | 100 | 400 | 50 | 0 | 0 | 550 |
| Cucumber Magnolia | 0 | 0 | 50 | 0 | 0 | 0 | 50 |
| Red Oak | 0 | 0 | 50 | 0 | 0 | 0 | 50 |
| Black Cherry | 100 | 50 | 0 | 0 | 0 | 0 | 150 |
| Black Birch | 0 | 0 | 0 | 0 | 0 | 14 | 14 |
| **Total** | **6100** | **750** | **900** | **50** | **0** | **72** | **7886** |

## Discussion

The main objectives for this evaluation were to determine the extent and impact of hemlock woolly adelgid, inventory the area, and evaluate the need for management activities within the hemlock grove of the Flight 93 National Memorial. Hemlock woolly adelgid is present in the stand and its distribution is patchy across the hemlock grove. Thirty-four percent of the hemlock

trees that could be evaluated had HWA present and 16.4 % of the overstory trees inventoried were dead hemlocks. We attributed the current hemlock tree mortality to overstocking. With a basal area per acre of 250.6 $ft^2$/ acre, 290 trees per acre, and a QSD of 17.1 inches, the stand is well above the stocking level for an even aged hemlock stand (figure 4). In an overstocked hemlock stand, early branch pruning occurs, tree crowns narrow and condense, growth slows (Godman and Lancaster 1990) and self-thinning (mortality) occurs. Even though eastern hemlock is considered one of the most shade tolerant of all tree species (Godman and Lancaster 1990) stands that contain over 200 $ft^2$ of basal area are considered heavily stocked (Lancaster, 1985). At these high densities tree mortality exceeds growth so net stand growth becomes negative. A fully stocked even aged eastern hemlock stand with a QSD of 17.1 inches should have between 80 and 90 trees per acre and a BA/Ac of 160 $ft^2$/acre (Lancaster, 1985).

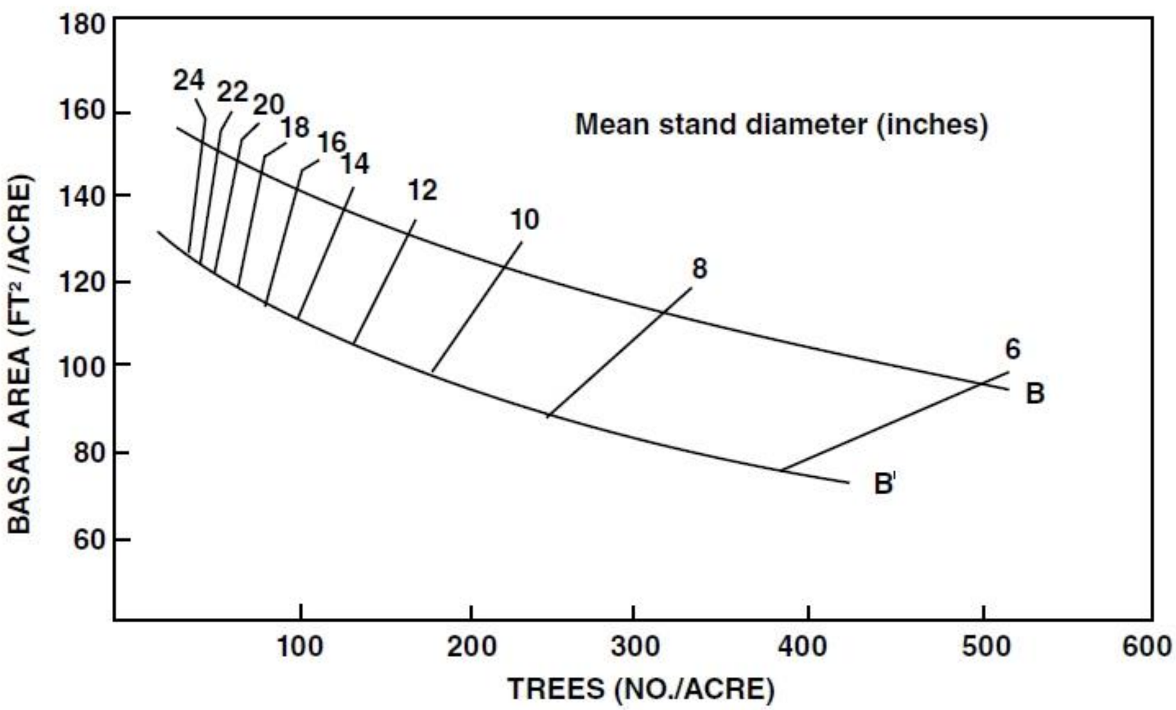


**Figure 4**. Residual stocking levels (B and B' levels) for even-aged hemlock stands based on number of trees, mean stand diameter, and basal area per acre. B level represents minimum residual stocking of stands with 30 % or more hemlock initially. B' level applies to stands with 15 - 29 % hemlock. (In mixed stands, the percentage of hemlock is based on a comparison of hardwood stems in the main crown canopy and the hemlock six inches DBH and larger in the overstory and understory positions (Lancaster, 1985).

Since the stand is currently well above the recommended stocking level, the hemlock trees present within the grove grow very slowly. The presence of HWA to the stand creates additional stress on the hemlock tress within the stand. Heavy to moderate dieback was observed in 20 % of the monitoring trees and four percent of the trees are showing a moderate level of

transparency. This reduction in crown is likely the result of a combination of this competition and feeding by HWA. HWA has piercing sucking mouth parts and feeds on the stored plant nutrients in the ray parenchyma cells (Young et al. 1995). Feeding by the adelgid causes needle loss and an increase in crown transparency, and the mortality of buds and branch tips (dieback; Cheah et al. 2004), which eventually leads to tree mortality. The presence of HWA in the hemlock grove raises concerns about the long-term stability and viability of eastern hemlock at the memorial.

With the arrival of HWA at the Flight 93 National Memorial land managers will be forced to respond to its impacts to some degree, regardless of the strategy they adopt. Falling woody debris from dead trees within the grove will present a threat to visiting family members. The eventual loss of eastern hemlock from the crash site will impact not only the historic preservation of the site but permanently alter the native forest ecosystem. Addressing these concerns will require a well-conceived management plan with specific goals and implementation mechanisms (e.g. management options (selected removal, chemical treatment), wood utilization, material disposal, replanting, and canopy replacement strategy).

Currently, the only available options for protecting eastern hemlock from HWA are individual tree chemical treatments. Treatments are limited by the biology and feeding behavior of HWA, its population densities, the site conditions (i.e. proximity to streams), accessibility and the limited application technology currently available. Insecticide treatments are effective, although they are conducted on an individual tree basis and can be both labor intensive and costly. Thus treatment strategies are typically focused in high value sites such as recreational or scenic areas. Classical biological controls such as predators and pathogens are being pursued by the USDA Forest Service but will likely take years to become effectively established. As such, preservation of hemlocks at the grove will require intensive monitoring and an aggressive chemical treatments strategy. Since HWA has been found on the Memorial it is recommend that a comprehensive hemlock management plan be developed and a chemical suppression/prevention treatment plan be put into place as soon as possible.

## Management Options

Three management options have been evaluated for managing HWA at the Flight 93 Memorial. The two intervention options are offered based on the following objectives: 1) protect all hemlock trees within the hemlock grove; and 2) protect hemlock but at a reduced density based on recommended stocking level guidelines. Each option is discussed below.

*No action option*

In this option hemlock woolly adelgid is allowed to infest eastern hemlock trees within the hemlock grove. Should this option be selected, it is likely that all eastern hemlock trees would be attacked and die as a result of HWA feeding. This would result in the loss of not only a high value collection of trees but would result in a hazard to family members visiting the grove, and a reduction in the overstory canopy. The majority of the seedlings and saplings on the site are green ash, red maple, and other hardwood species, therefore the no action option will likely result in the conversion of the stand from an eastern hemlock stand to a mixed hardwood stand.

## Intervention Options

*Foliar chemical treatments*

Aerial spray using horticultural oil or insecticidal soap is not an option because aerial sprays could not provide the needed "saturation" necessary to ensure that the insecticide adequately covers the insect. Aerial spraying with more toxic insecticides (e.g. malathion or diazinon) would have very significant, unacceptable impacts on a wide range of non-target insects and other animals and limited control benefits (Evans 2000). Application of insecticides using ground spraying equipment is generally limited to areas accessible to hydraulic spray equipment and areas where over spray or runoff would not contaminate streams, lakes or ponds. Backpack sprayers could be effectively used for foliar treatment of infested seedlings and saplings to protect regeneration.

*Systemic Insecticides*

Several systemic insecticides labeled for adelgids can be injected (e.g. imidacloprid, dicrotophos), implanted (e.g. acephate) or sprayed on the bark (e.g. dinotefuran) or foliage of hemlock trees. Imidacloprid is by far the most common systemic insecticide being used to control HWA and is applied as a soil drench, truck injection, foliar treatment or soil application. These insecticides are absorbed and trans-located by the vascular system of the tree to feeding adelgids and will effectively suppress HWA populations (Doccola et al. 2003, Webb et al. 2003, Evans 2000, Steward and Horner 1994, McClure 1992).

*Biological control*

There are no known parasites of adelgids. There are three predatory beetles that have been released againist the HWA: *Sasajiscymnus tsugae* (Sasaji & McClure: Coleoptera: Coccinelidae), Scymnus sinuanodulus (Yu & Yao; Coleoptera: Coccinelidae) and *Laricobius nigrinus* Fender (Coleoptera: Derodontidae). Each with its own unique dispersal habits, reproductive potential, feeding behavior, and suitable climate regimes. They are all fairly host specific. Releases are usually done in infested hemlock stands found along the leading edge, or

in areas where hemlocks are still healthy and HWA densities have not yet overwhelmed the trees. The release and establishment of HWA natural enemies is not likely to provide any short term control of HWA. This longterm approach is still experimental and will likely require a complex of natural enemies to maintain HWA below damaging levels. It may be years before these predators can self-perpetuate sufficiently before any level of success can be determined.

## Alternatives

With the previously described options in mind, the following alternatives are offered:

| | |
|---|---|
| Alternative 1. | No action |
| Alternative 2. | Chemical treatment of all hemlock trees (up to limits on active ingredients per acre) within the grove. |
| Alternative 3. | Chemical treatment of selected understory and overstory hemlock trees to recommended stocking level and the release of biological control agents. |

## Recommendations

Alternative three is recommended based on the following considerations.

1) The hemlock grove is currently overstocked. Trees will continue to die as a result of competition. Reducing the TPA and density will increase the overall health of the stand and allow for selection of the best growing stock and promote the sustainability of the hemlock stand.

2) Chemical treatments are recommended for HWA control on individual, hemlock trees in the hemlock grove. Insecticides have been shown to be an effective treatment against the hemlock woolly adelgid and will allow for the retention of eastern hemlock within the grove.

3) Release and establishment of *Sasajiscymnus tsugae*, *Scymnus sinuanodulus*, and *Laricobius nigrinus* predatory beetles is also recommended in infested areas on hemlocks that are not in close proximity to chemical treatments. The establishment of these natural enemies offers the opportunity for long-term control and may minimize the need for repeated chemical treatments in future years.

## Species Evaluation

*Hemlock Woolly Adelgid*

HWA is believed to have been introduced into the eastern United States from Japan (Havill and Foottit. 2007) sometime before 1951 on nursery stock. It was first discovered on eastern hemlock trees in a municipal park that had previously been a private estate (Souto et al. 1996, Ward et al. 2004). Over the next 30 years HWA slowly spread through the Mid-Atlantic States (Souto et al. 1996). By the late 1980s and 1990s HWA population had expanded rapidly and was reported to be causing widespread mortality (Cheah et al. 2004). HWA is currently established in 17 eastern States from Georgia to Maine.

*Life Cycle*

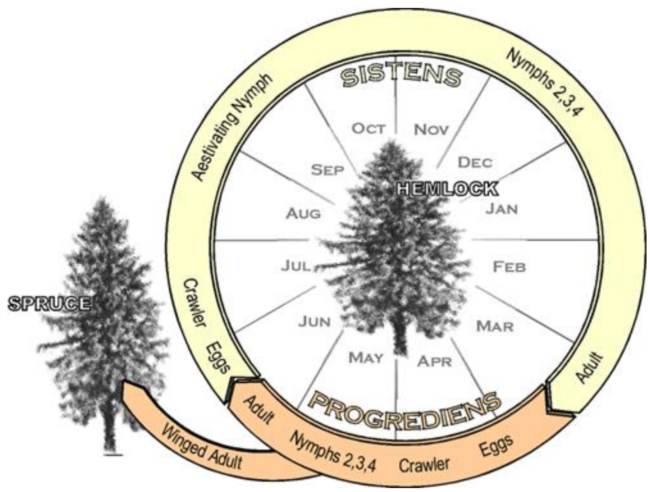


**Figure 5**. Life cycle of the hemlock woolly adelgid on hemlock in North America (Ward et al. 2004)

HWA has a complex life cycle involving both sexual and asexual stages on both hemlock and spruce (figure 5; McClure 1989). The life cycle on eastern hemlock is bivoltine including a "sistens" or wingless winter generation that starts in late spring and lasts for 9 to 10 months (McClure 1989) and a "progrediens" or spring generation that starts in the early spring. The progredien generation is composed of both winged (sexuparae) and wingless offspring and lasts for about three months (Ward et al. 2004). The winged generation is the sexual migratory stage which leaves hemlock to find spruce (McClure 1987). The percentage of the population of progrediens is strongly density dependent; as the tree health declines and preferred feeding sites (new growth) is reduced the percentage of winged adults increases (McClure 1991). Because of the lack of a suitable spruce species in the eastern United States the production of the winged form results in a substantial loss of individuals from the spring generation (McClure 1989). HWA has a high reproductive potential with each adult producing up to 300 eggs (McClure et al. 2001). The eggs hatch into first instar mobile crawlers, which are active for one to two days, before settling or being dispersed (McClure 1987, Ward et al. 2004). Once settled the nymph inserts its stylet and feeds on the xylem ray parenchyma cells at the base of the hemlock needles (Young et al. 1995). The adelgid then develops through four instars before becoming an adult (McClure 1989).

*Feeding Impact*

The combination of two annual generations, a high reproductive capacity, and the lack of natural enemies (Van Driesche et al. 1996, Wallace and Hain 2000, Cheah et al. 2004) gives HWA the

ability to increase rapidly in numbers (McClure 1989). Feeding can quickly lead to needle loss, dieback and mortality (Cheah et al. 2004). Feeding by the adelgid restricts the uptake and movement of water (McClure 1995), which reduces the trees energy reserves (Ward et al. 2004) and can lead to tree mortality in 4-7 years (Orwig and Foster 1998, McClure et al. 2001), although some trees can last more than 10 years (Souto et al. 1996, Paradis et al. 2008). All life stages of hemlock, from seedling to mature old-growth trees are fed upon (McClure 2001).

*Dispersal and Spread*

HWA spreads mainly as eggs and crawlers which are transported by wind, birds, deer, and other forest-dwelling mammals (McClure 1990, Cheah et al. 2004, Ward et al. 2004). It can also be moved on infested nursery stock or during logging and recreational activities (McClure 1995, Gibbs 2002, Ouellette 2002). Roads, hiking areas and riparian areas have all been implicated in the long-distance spread of the adelgid by humans and birds (Koch et al. 2006). Recent evidence suggests that the current rate of spread is between 8-16 km per year (Evans and Gregoire 2007). As of 2011, 47 % of the native range of eastern hemlock is infested with HWA (A. Steketee, USDA Forest Service, personal communication).

*Eastern Hemlock*

Eastern hemlock, *Tsuga canadensis* (L.) Carr, is an extremely shade-tolerant, monoecious, slow-growing, late successional conifer with a dense, evergreen crown and that strongly influences its environment and other species (Ward and McCormick 1982, Godman and Lancaster 1990, Evans et al. 1996, Quimby 1996, Evans 2000). Eastern hemlock has a conical crown with horizontal-to-pendulous branches (Ruth 1974) and 2-ranked needles (Dirr 1998). It exhibits relatively low branch shedding (Kenefic and Seymour 2000), and retains its needles for an average of three years (Barnes and Wagner 1981).

Eastern hemlock is a relatively long-lived species with a life span of over 800 years (Godman and Lancaster 1990). Seed production usually begins when trees are 20-30 years of age (Ruth 1974). It is a frequent and abundant cone producer (Crow 1996), with good crops being produced every 2 to 3 years (Frothingham 1915, Ruth 1974).

*Native Range*

Eastern hemlock is widely distributed in North America from Nova Scotia across southern Ontario to northern Minnesota, and south to Alabama along the Appalachian Mountains (Brisbin 1970, Godman and Lancaster 1990, Quimby 1996). Hemlock generally grows in areas with cool humid climates (Godman and Lancaster 1990, McWilliams and Schmidt 2000). Annual precipitation ranges from 74 cm to more than 127 cm across the range of eastern hemlock (McWilliams and Schmidt 2000). It grows at elevations from sea level to 730 m in the

northeastern and northern areas, from 300 to 910 m on the Allegheny Plateau and from 610 to 2036 m in the southern part of its range (Hough 1960, Eyre 1980, Godman and Lancaster 1990).

*Growth and Associated Species*

Hemlock can occur in pure stands (Eyre 1980), or mixed with other species. On favorable sites, it usually forms a climax position (Brisbin 1970) while on sites with rich in nutrients, it can be out competed by hardwoods (Kotar 1996). In pure stands, undergrowth vegetation can be sparse (Eyre 1980) due to intraspecific allelopathy (Ward and McCormick 1982) and to the dense evergreen crown of hemlock which intercepts both light and precipitation. Because of this dense canopy in hemlock stands the microclimate is cooler than under hardwoods (Tubbs 1996). This distinct microclimate provides an important habitat for a wide variety of wildlife (Evans 2000). In the northeastern United States 96 bird and 47 mammal species have been found to be associated with eastern hemlock forests (Yamasaki et al. 2000). This includes 23 species of small mammals, 14 species of wide ranging carnivores, 10 species of amphibians, and 7 species of reptiles (Degraaf et al. 1992). Hemlock forests can also be a critical factor in the support of native brook trout populations, where it maintains cool stream temperatures and stabilizes stream flows (Evans et al. 1996, Quimby 1996). Eastern hemlock fills a unique ecohydrological role because it transpires throughout the year and it provides stable water fluxes within a watershed and high water flux patterns in the spring, reducing nutrient loss and decreasing watershed discharges (Ford and Vose 2007).

## Chemical Evaluation

Imidacloprid Neonicotinoids represent the most effective insecticide for controlling piercing sucking insects such as aphids, leafhoppers, planthoppers, thrips, fleas and some coleopteran (e.g. leaf beetles) and selected species of lepidopteran and dipteran pests (Mullins 1993, Tomizawa and Casida 2005, Elbert et al. 2008). Neonicotinoids comprise seven different commercially available products: acetamiprid, clothianidin, dinotefuran, imidacloprid, nitenpyram, thiacloprid and thiamethoxam (Tomizawa and Casida 2005, Elbert et al. 2008) and have been the only new class of insecticides developed since the 1970s (Tomizawa and Casida 2005). The name neonicotinoids was adopted to show the structural and mode of action differences from nicotine and nicotine-related compounds (Matsuda et al. 2009). The factors that contribute to the success of this class of insecticides is their plant systemicity (Elbert et al. 2008), and mode of action, which offers no cross-resistance to other conventional long-established insecticides (Jeschke and Nauen 2008).

Imidacloprid, 1-[(6-chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine, is a broad spectrum neonicotinoid insecticide with low to moderate mammalian toxicity (Mullins 1993), high

insecticidal potency (Lansdell and Millar 2000, Tomizawa and Casida 2005), and a good environmental and toxicological profile (Silcox 2002). As a result it has become one of the world's most widely used insecticides (Silcox 2002, Jeschke and Nauen 2008). It is both a systemic and contact insecticide (Mullins 1993) and has become the preferred pesticide for controlling HWA (Smith and Lewis 2005, Eisenback et al. 2008).

Imidacloprid was first synthesized by Nihon Bayer Agrochem in 1985 (Elbert et al. 1998), and first registered in the United States under the tradename Merit® in 1994 (Silcox 2002). It is classified in toxicity classes II (moderately toxic) and III (slightly toxic) by the Environmental Protection Agency. Imidacloprid is sold under a variety of tradenames: Admire®, Advantage®, Gaucho®, Premise®, and Touchstone®. In 2006, imidacloprid came off patent and became generic (Jeschke and Nauen 2008).

*Mode of Action*

Imidacloprid has a mode of action similar to that of the botanical product nicotine, functioning as a fast-acting insect neurotoxicant (Schroeder and Flattum 1984) that binds to the post-synaptic nicotinic acetylcholine receptors (nAChRs) of the insects' central nervous system (Jeschke and Nauen 2008). Imidacloprid mimics the action of acetylcholine, and thereby heightens, then blocks the firing of the postsynaptic receptors with increasing doses (Schroeder and Flattum 1984, Felsot 2001). Acetylcholine is the major excitatory neurotransmitter of insect's central nervous system (Lansdell and Millar 2000, Tomizawa and Casida 2003); it binds and then is degraded by the inactivating enzyme acetylcholine esterase (Breer and Sattelle 1987). Because imidacloprid is not removed by acetylcholine esterase, it causes substantial disorder within the nervous system leading to tremors, paralysis and in most cases death (Mullins 1993, Smith and Krischik 1999). Toxicity studies have demonstrated that this insecticide is neither carcinogenic nor teratogenic (Mullins 1993).

*Translocation in Plants*

Translocation experiments from a number of vascular plants (e.g. corn, cotton, and eggplant) have shown that imidacloprid has good translaminar movement (Elbert et al. 2008) and excellent xylem mobility to shoots and leaves and poor phloem mobility to storage organs, roots and fruits; as a result the highest residues are expected in the older leaf portions of the plant (Sur and Stork 2003). The systemic properties of imidacloprid are a function of its physical properties, mainly its high water solubility (Cox et al. 1997, Oi 1999), low n-octanol/water partition coefficient ($K_{o/w}$) (Nemeth-Konda et al. 2002), low vapor pressure (Lagalante and Greenbacker 2007) and dissociation coefficients ($K_d$) (Sur and Stork 2003).

*Metabolism in Plants*

Most of the imidacloprid administered to plants is metabolized, with little of the parent compound imidacloprid remaining (Nauen et al. 1998). The metabolites formed are dependent on the method of application (Nauen et al. 1998) and the species of plant treated (Sur and Stork 2003). Because of the variety of functional groups present in the imidacloprid molecule (figure 3), it undergoes degradation by a number of different pathways and creates a number of different metabolites (Tomizawa and Casida 2003). Metabolites vary in their biological activity against certain insect species (Nauen et al. 1998, Nauen et al. 1999, Nauen et al. 2001), with some being active against mammalians and deactivated against insects (Tomizawa et al. 2000).

*Metabolism in Soil*

Under field application conditions only a small amount of the applied pesticide ever reaches the target; the majority is released into the soil, and must be degraded photochemically, abiotically and biologically (Wamhoff and Schneider 1999). For Imidacloprid, sorption-desorption processes along with photodegradation and hydrolysis determine the distribution and fate in the soil-water environment (Cox et al. 1997). Imidacloprid undergoes various physio-chemical processes when applied to the soil (Nemeth-Konda et al. 2002).

As with the metabolism in plants, imidacloprid and its metabolites are affected by application method and soil properties (e.g. pH and clay content), with different metabolites having different sorption rates based on the amount of organic carbon present (Cox et al. 1997) and the length of time in the soil (Oi 1999). Insecticides that are sorbed to soil particles are not bioavailable, so they first must be desorbed from the soil into solution to be bioavailable (Koskinen et al. 2001). Desorption for imidacloprid and its metabolites has been shown to be hysteric (Cox et al. 1997). Hysteric desorption indicates that there is a higher desorption coefficient than sorption for some of the metabolites (Oi 1999), making it more difficult for these molecules to reach the target (tree roots) (Cox et al. 1997). The half life of imidacloprid in soil is between 48-190 days, depending on the formulation, application rate and amount of ground cover (Scholz and Spiteller 1992). In neutral or acidic water, imidacloprid is stable and slowly hydrolyzed (Liu et al. 2006).

*Potential non-target effects of imidacloprid*

Due to the systemic properties of imidacloprid the potential for non-target effects on arthropods may be expected. Imidacloprid is highly mobile and depending on treatment (e.g. drench, soil application) movement to other non-target plants in the treatment area should be expected. As mentioned in the section on mode of action imidacloprid has high insecticidal potency and works through activation of the nicotinic acetylcholine receptors, causing paralysis and eventually death. Therefore any arthropods (beneficial or otherwise) that ingest plant material (e.g. foliage,

sap, seeds, and propolis) or are exposed to a foliar application in a treatment area are likely to demonstrate lethal or sub-lethal effects

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